

**Project Title:**  
**Whale Hearing Models**  
**ONR Award No: N00014-00-10905**  
**Final Report**  
**Total Award Period: 18 August 2000 – 30 January 2005**  
**Final Reporting Period: 21 June, 2003 – 20 June, 2005**

Darlene R. Ketten, Ph.D.  
Senior Scientist, Biology Department, MS# 50  
Woods Hole Oceanographic Institution  
Woods Hole, MA 02543  
Asst. Professor, Department of Otology and Laryngology  
Harvard Medical School  
phone: 508-289-2731 (WHOI) email: dketten@whoi.edu

David Mountain, Ph.D.  
Professor of Biomedical Engineering  
Boston University  
44 Cummington St.  
Boston, MA 02215  
phone: 617-353-email: dcm@bu.edu

**DISTRIBUTION STATEMENT A**  
**Approved for Public Release**  
**Distribution Unlimited**

#### **SCIENTIFIC AND TECHNICAL OBJECTIVES**

The specific objective of this project was to develop biophysically based models of the inner and middle ear of a range of marine mammals to allow us to estimate audiograms from anatomical and mechanical measurements.

This project was designed to provide modular data to be integrated with the methodologies and partnership projects developed under the ONR Effect of Sound in the Marine Environment (ESME) Program.

The effort involved an integration of anatomical and physiological data. Anatomical analyses (WHOI/D.R. Ketten) characterized head, middle, and inner ear structures of representative odontocete species. Physiological Modeling (BU/ David Mountain) implemented auditory response models using the anatomical data. This is the requisite first-step towards developing species-specific TTS models.

#### **ACCOMPLISHMENTS AND RESULTS**

The accomplishments consist primarily of the following:

- Completion of scans for representative species of porpoises, dolphins, humpback whales, sea lions, and beaked whales (**Ketten et al. 2003; Ketten 2004; Norman et al 2005; Chadwick et al 2006**)
- Biochemical analyses of fatty tissues associated with the lower jaw and ear regions for harbour porpoises and two beaked whale species (**Koopman et al 2006**)
- Sound speed measures for harbour porpoises (**Prasad, 2004**)
- Middle ear stiffness measures in porpoises, dolphins, and one beaked whale species (**Mountain et al 2003; Miller et al 2006**)
- Comparisons of fresh, fixed and frozen tissues from two control species to determine fidelity of measures across species and fixation conditions (**Miller et al 2006**)

WHOI and BU teams worked jointly to identify anatomical features that have the best predictive value for acoustic responses; e.g., range and sensitivity, for both marine and land mammal ears. Species-specific

databases were developed for heads, middle ears and inner ears to facilitate export to ESME modules and web-based distribution as well as additions and revisions of prior, limited data on cetaceans as more individual and species hearing data become available.

Data obtained by the WHOI group (Ketten Lab) were directed at developing appropriate protocols to provide consistent interspecies data sets and at obtaining, via these protocols, complete head and inner ear anatomical descriptors that could be used for finite element modeling transmission characteristics for underwater signals.

Complete data sets were obtained for whole heads and/or ears of harbour porpoises, bottlenosed dolphins, humpback whales, right whales, and sea lions. CT and MRI images as well light and electron microscopic measures were completed for 1 or more specimens of each species.

In addition, measurements of the inner ears of chinchillas and cats were obtained in order to provide comparative data of the inner ear scalae, basilar membrane, and organ of Corti elements in common laboratory animals.

Sound speed measurements were obtained via Time of Flight techniques for excised tissues of harbour porpoises in a system designed by Dr. David Brown of U Mass at Dartmouth, Bioengineering Dept.

Beaked whale specimens in this project were also analyzed by Dr. Heather Koopman during her tenure as a postdoctoral fellow at WHOI to determine whether there are significant variations in the biochemical and structural features of jaw fats in beaked whales vs other odontocetes.

### **Physiological Modeling**

The BU team (D. Mountain laboratory) was successful in obtaining direct stiffness measures of the middle ear from 2 species and demonstrated comparable measures of some inner and middle ear structures were possible from fresh, formalin fixed, and previously frozen material, which substantially broadens the potential data base of ears. The BU team also adapted existing procedure and hardware for exposure of the basilar membrane in the exceptionally large and dense odontocete periotics and for direct displacement and stiffness measures of both the middle and inner ear components in odontocetes comparable to those previously obtained in land mammals.

### **Middle Ear Anatomy**

A number of different hypotheses have been put forth about how the cetacean middle ear might function but many lack biophysical plausibility. To take a fresh look at the middle ear anatomy in odontocetes, we used microCT scanner to scan ears from our two control species, harbor porpoise and bottlenose dolphin.

The major attachment points for the malleus-incus complex are the processus gracilis and the minor process of the incus. These points define the most likely axis of rotation for the malleus-incus complex. Since the processus gracilis is fused with the tympanic bone, it appears that this structure acts as a torsional spring which may help to stiffen the middle ear. Although the shapes of the incus and malleus differ considerably from terrestrial mammals, this arrangement of the incus and malleus is very similar to that found in high-frequency terrestrial mammals.

The dolphin stapes is attached to the major process of the incus which acts as a lever arm. The tympanic ligament attaches to a longer lever arm on the malleus. The tensor tympani muscle attaches to the same point, but from the opposite side, and is oriented so as to pull on the tympanic ligament when it contracts. This orientation of the tensor tympani with respect to the tympanic ligament is the same as that found in terrestrial mammals. The stapedial muscle is oriented at right angles to the motion of the stapes which is

also the same orientation as that found in terrestrial mammals. Our anatomical studies provide further support for the hypothesis that the cetacean middle ear works in a fashion very similar to that of high-frequency terrestrial mammals and that the tympanic ligament plays a major role in producing middle ear motion in response to sound.

The fact that the odontocete middle ear appears to function in a manner similar to that found in terrestrial mammals means that generic biophysical models of middle ear function can be used to predict middle ear function in cetaceans and get an estimate of low-frequency hearing sensitivity through simple measurements of middle ear stiffness.

Middle ear measures that were completed in this grant employed a piezoelectric actuator that produces a sinusoidal displacement of the stapes. The force sensor measures the stapes force and stiffness is computed by taking the ratio of force to stiffness. The low-frequency cutoff of the audiogram is a power function of middle-ear acoustic stiffness in terrestrial mammals. Odontocetes follow the general mammalian trend for high frequency species; the middle-ear acoustic stiffness for bottlenose dolphin and for harbor porpoise is close to the regression line for terrestrial mammals. This suggests to us that the cetacean middle ear functions in a manner similar to that of other mammals

### ***Basilar Membrane Mechanics***

The range of hearing in mammals and especially the high-frequency limit is believed to be determined by the basilar membrane frequency-place map. In terrestrial mammals, the basilar membrane near the base of the cochlea is much stiffer than it is near the cochlear apex. As a result, the basal portion of the membrane responds best to high frequencies and the apical portion of the membrane responds best to low frequencies.

To measure basilar membrane stiffness in cetaceans, we have used a force probe that is similar in concept to that used for the middle ear measurements but which is much more sensitive. The dolphin stiffness gradient is very similar to that for gerbil but exhibits a higher stiffness. If basilar membrane mechanics in the two species are similar, the higher stiffness for dolphin is to be expected since the high-frequency limit for the bottlenose dolphin is about 2.5 times that for gerbil.

Von Békésy (1960) published data for basilar membrane volume compliance from a number of different species. In Figure 5 we have converted our gerbil and dolphin stiffness data into volume compliance and plotted our data along with the von Békésy data. All of the species show similar compliance gradients and the dolphin curve exhibits the lowest compliance (highest stiffness) as would be expected for a high frequency ear.

## **IMPACT/APPLICATIONS**

Our mechanical and anatomical measurements in control species support the hypothesis that the cetacean middle ear and cochlea function in a manner very similar to that of terrestrial mammals. This means that the computational models that we have developed to predict hearing function in terrestrial mammals can be extended directly to cetaceans. Our next step is to extend the middle ear and cochlear measurements to species of special concern (c.g. beaked whales) and to use our computational models to predict audiograms for these species.

### **National Security**

These data will assist in designing effective noise mitigation measures and may be useful in determining the mechanisms involved in beaked whale strandings in association with naval exercises.

### **Quality of Life**

This research is a requisite step in determining how to avoid or ameliorate potential sound impacts from human generated noise, intentional as in sonar or seismic explorations, or auxiliary as from ship generated noise, in our oceans.

### Science Education and Communication

Both laboratories involved in this effort began development of web-accessible data bases and publicly accessible representative samples of this work.

The WHOI laboratory is developing a website featuring CT images and reconstructions for representative marine mammal species and can incorporate any new whale data that are releasable to the public. The scan data are archived in multi-platform compatible DICOM formats for broad application..

BU has already begun producing a web-site for review of available audiograms as part of their on-going EarLab project and has the infrastructure to extend their site to incorporate the inner ear models as a step towards a manageable, ESME-compatible model that can be run from the website that includes marine species for which there are reliable hearing data as well as sample sources with appropriate distance effects in their renditions, including biologic, commercial, exploratory, and military sources. The databases are expected to be open architecture and structured for ease of export and cross-application access

### RELATED PROJECTS

Not applicable

### PUBLICATIONS (acknowledging support of this grant)

#### Referred Journal Publications

- 2003 Mountain, D.C., Hubbard, A.E., Ketten, D.R. and O'Malley, J. The helicotrema: Measurements and models In: Biophysics of the Cochlea: from Molecules to Models. A.W. Gummer, E. Dalhoff, M. Nowotny, M. Scherer (eds.). World Scientific, Singapore, pp. 393-399.
- 2003 Ketten, D.R., T. Rowles, S. Cramer, J. O'Malley, J. Arruda, and P. Evans. Cranial Trauma in Beaked Whales. Proceedings of the Workshop on Active Sonar and Cetaceans, *ECSN*, no. 42, pp. 21-27.
- 2004 Ketten, D.R. Marine Mammal Auditory Systems: A Summary of Audiometric and Anatomical Data and Implications for Underwater Acoustic Impacts. *Polarforschung*, 72. Jahrgung, Nr. 2/3, pp. 79-92.
- 2006 Cox T.M., T.J. Ragen, A.J. Read, E. Vos, R.W. Baird, K. Balcomb, J. Barlow, J. Caldwell, T. Cranford, L. Crum, A. D'Amico, G. D'Spain, A. Fernández, J. Finneran, R. Gentry, W. Gerth, F. Gulland, J. Hildebrand, D. Houser, T. Hullar, P.D. Jepson, D. Ketten, C.D. MacLeod, P. Miller, S. Moore, D. Mountain, D. Palka, P. Ponganis, S. Rommel, T. Rowles, B. Taylor, P. Tyack, D. Wartzok, R. Gisiner, J. Mead, L. Benner. Understanding the Impacts of Anthropogenic Sound on Beaked Whales, *Journal of Cetacean Research and Management*, vol. 7(3), pp. 177-187.
- 2006 Miller, B.S., Zosuls, A.L., Ketten, D.R. and Mountain, D.A. Middle ear stiffness of the bottlenose dolphin (*Tursiops truncatus*) *IEEE Journal of Oceanic Engineering*, vol. 31(1), pp. 87-94
- 2006 Koopman, H.N., S.M. Budge, D.R. Ketten, and S.J. Iverson. The topographical distribution of lipids inside the mandibular fat bodies of odontocetes: Remarkable complexity and consistency. *IEEE Journal of Oceanic Engineering*, vol. 31(1), pp. 95-106.
- 2006 Chadwick, R.S., Manoussaki, D., Dimitriadis, E.K., Shoelson, B., Ketten, D.R., Arruda, J., O'Malley, J.T. Cochlear coiling and low-frequency hearing. (*Passive and Active Structural Acoustic Filtering in Cochlear Mechanics*, in press)

### Book Chapters/Technical Reports/ Theses

- 2003 Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals, Ocean Noise and Marine Mammals. National Research Council, 204 pages.
- 2004 International Whaling Commission, Scientific Committee Report Annex K: Report of the Standing Working Group on Environmental Concerns, Marine Mammal Hearing and Evidence for Hearing Loss, Appendix 4 (pp 27-31).
- 2004 Prasad, K. SOUND SPEED INVESTIGATION OF DOLPHIN TISSUE. M.S Thesis in Electrical and Computer Engineering University of Massachusetts Dartmouth, Acoustic Research Laboratory, College of Engineering.
- 2005 Norman, S.A., S. Raverty, B. McLellan, A. Pabst, D.R. Ketten, M. Fleetwood, J.K. Gaydos, B. Norberg, L. Barre, T. Cox, B. Hanson, and S. Jeffries Multidisciplinary Investigation of Harbor Porpoises (*Phocoena phocoena*) Stranded in Washington State from 2 May – 2 June 2003 Coinciding with the Mid-Range Sonar Exercises of the USS SHOUP. NOAA Northwest Fisheries. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, NOAA Technical Memorandum NMFS-NWR-34.\

### Short Communications/Refereed Abstracts of Meetings

- 2003 Hammock, J., Lytwyn, K., Dacey, J., Ketten, D. 2003. A Behavioural Olfactogram of the Sea Otter, *Enhydra lutris*. Oral presentation given at the Society for Marine Mammalogy Biennial Conference, Greensboro, NC
2003. Fish, F. E. and Ketten, D. R. Examination of three-dimensional geometry of cetacean flukes using CT-scans. Annual Meeting of the Society for Integrative and Comparative Biology.
- 2003 Koopman, H. N., Budge, S. M., Ketten, D. R., and Iverson, S. J. Sound reception by beaked whales and porpoises: Implications of variation in lipid composition of jaw fats. 17th Conference of the European Cetacean Society, Las Palmas de Gran Canaria.
- 2003 Koopman, H. N., Budge, S. M., Ketten, D. R., and Iverson, S. J. The influence of phylogeny, ontogeny and topography on the lipid composition of the mandibular fats of toothed whales: Implications for hearing. Symposium on Environmental Consequences of Underwater Sound, San Antonio, Texas.
- 2003 Moein Bartol, S. and Ketten, D. R. Auditory Brainstem Responses of Multiple Species of Sea Turtles. Symposium on Environmental Consequences of Underwater Sound, San Antonio, Texas.
- 2003 Ketten, D. R. Beaked Whale Heads: Is There a Smoking Sonar? Symposium on Environmental Consequences of Underwater Sound, San Antonio, Texas.
- 2003 Mountain, D., D. Ma, A. Zosuls, D. Ketten, and A. Hubbard Models of Whale Auditory Function. Symposium on Environmental Consequences of Underwater Sound, San Antonio, Texas.
- 2003 Reidenberg, J., Ketten, D., Laitman, J. Effect of blast derived shock waves on the appearance of odontocete respiratory tissues, Fourteenth Biennial Conference on the Biology of Marine Mammals. Vol. 15:136
- 2003 Koopman, H.N., Budge, S. M., Ketten D. R., and Iverson, S. J. Focusing sound to the odontocete ear: Does the complex topographical arrangement of specific lipids form a wave guide through the mandibular fats? Fourteenth Biennial Conference on the Biology of Marine Mammals.
- 2003 Walsh, E.J., Ketten, D.R., Wang, L.M., Armstrong, D.L., Curro, T., Simmons, L.G. and McGee, J.. Bioacoustics in *Panthera tigris*. Soc. Neurosci., 33rd Annual Meeting, New Orleans, LA.
- 2003 Edds Walton, P., D.R. Ketten, and R. Fay. Extreme Variations in Skull Density of Toadfish, *Opsanus Tau*, Acoustical Society of America., Austin, TX
- 2003 Walsh, E.J., Ketten, D.R., Wang, L.M., Armstrong, D.L., Curro, T., Simmons, L.G. and McGee, J. (2003). Bioacoustics in *Panthera tigris*. Soc. Neurosci., 33rd Annual Meeting, New Orleans, LA.
- 2003 Reidenberg, J.S., D.R. Ketten, and J.T. Laitman Effect of blast derived shock waves on the appearance Assoc. for Rsch. in Otolaryngology.

- 2003 Ketten, D.R. Effects of noise on Hearing: Marine mammal evidence and analyses *Invited paper*, European Cetacean Society, Workshop on Effects of Sonar, Gran Canarias.
- 2003 Ketten, D.R. Underwater Ears and the Physiology of Impacts: Is it Don Ho, Smoking Sonars, or What? *Invited paper*, Fourteenth Biennial Conference on the Biology of Marine Mammals
- 2004 Ketten, D.R. Cranial Trauma: Evidence for and against acoustic impacts. *Invited paper*, IWC, Sorrento, Italy.
- 2004 Ketten, D.R. Marine Mammal Hearing and Evidence for Hearing Loss, *Invited paper*, IWC Workshop on Acoustics, Sorrento, Italy.
- 2004 Ketten, D.R., Dolphin, W.F., Williams, R. Arruda, J.O'Malley, J. *In vivo* imaging correlated with otoacoustic emissions as a metric for ear disease in seals. *Invited paper* Acoustical Society of America, San Diego.
- 2004 Parks, S.E., D.R. Ketten, J.T. O'Malley, and J. Arruda Hearing in the North Atlantic right whale: Anatomical predictions. Acoustical Society of America, New York, NY.
- 2004 S.O. Newburg, S.O., B.S. Miller, A.L. Zosuls, D.R. Ketten and D.C. Mountain. Biomechanics of Dolphin Hearing. Proceedings of the Biomedical Engineering Society Annual Meeting.
- 2004 Smith, M. E., Ketten, D.R., Hastings, M. C., and Popper, A. N. Head Holes Help Hearing: the Auditory Periphery of *Otocinclus* Catfish. Association for Research in Otolaryngology
- 2004 Webb, J.F., Tricas, T.C., Shearman, E. Walsh, R. Ketten, D.R., and Herman, J.L. , Ear and Swim Bladder Morphology in Chaetodontid Fishes: Adaptations for Enhancement of Hearing. International Congress of Vertebrate Morphology, Boca Raton, FL. ? *J. Morphology*. 260(3): 339
- 2004 Prahl, S., Ketten, D.R., Lucke, K., O'Malley, J., and Siebert, U. Assessing the Potential Impact of Sound on Harbour Porpoises in the North and Baltic Sea: A Histo-Pathological Attempt. European Cetacean Society.
- 2004 Reidenberg, J.S., Ketten, D.R., and Laitman, J.T. (2004) Effects of blast pressure exposures on the dolphin and porpoise larynx. American Association of Anatomists: Experimental Biology Meeting, FASEB Journal, p.A33.
- 2004 Montie, E., M. Moore, D. Ketten, J. Arruda, A. Bogomoini, and M. Hahn. Using Magnetic Resonance Imaging (MRI) to Obtain Shpaes and Sizes of Pinniped and Cetacean Brain Regions that Depend on Thyroid Hormones for Maturation. EPA STAR Graduate Fellowship Conference.
- 2004 Montie, E., M. Moore, D. Ketten, J. Arruda, S.Cramer, I. Fischer, K.Touhey. K.Patchett, A. Bogomoini, B. Lentell, B. Sharp, G. Early, and M. Hahn. Anatomy, Three-Dimensional Reconstructions, and Volume Estimation of the Brain of the Atlantic White-sided Dolphin (*Lagenorhynchus acutus*) from Magnetic Resonance Images. NE Stranding Conference
- 2004 Walsh, E.J., Ketten, D.R., Wang, L.M., Armstrong, D.L., Curro, T., Simmons, L.G. and McGee, J.. Temporal Bone Anatomy in *Panthera tigris*, Acoustical Society of America, New York.
- 2004 Ketten, D.R., J. Simmons, A.E. Hubbard, and D. Mountain. Dolphin and Bat Sonar: Convergence, Divergence, and Parallelism. Acoustical Society of America, New York.
- 2004 Raverty, S, S Norman, M Fleetwood, J Gaydos, D Ketten, A Pabst, W McLellan, L Barre, B Hanson, S Jeffries, D Lambourn, S Cramer, T Cox, and B Norberg Pathologic findings in Harbor Porpoises (*Phocoena phocoena*) stranded in Washington State 2 May to 2 June 2003 coincident with the mid-frequency sonar excercises by the USS Shoup. American College of Veterinary Pathology
- 2004 Hammock, J., Lytwyn, K., O'Malley, J., Ketten, D.R., Dacey, J.W.H. 0.000000000005 if by Land, 0.000000004 if by Sea; the Chemical Ecology of Olfactory Sensitivity. Poster presented at the Biennial Conference of the European Chemoreception Research Organization, Dijon, France
- 2004 Hammock, J., Lytwyn, K., O'Malley, J., Ketten, D.R., Dacey, J.W.H. Tools and Context: The Nasal Morphology and Chemical Ecology of Olfactory Sensitivity. Poster presented at the Japanese Association for the Study of Smell and Taste/International Symposium on Olfaction and Taste Conference, Kyoto, Japan

- 2004 Hammock, J., Lytwyn, K., Dacey, J., Ketten, D., O'Malley, J. 2004. Chemical Ecology of Olfactory Repertoire. Oral presentation given at the American Society of Mammalogists Conference, Arcata, CA
- 2005 Norman, SA, B. Norberg, L. Barre, S. Raverty, J.K. Gaydos, D.R. Ketten, S. Cramer, M. Fleetwood, W.A. McLellan, A. Pabst, T. Cox, B. Hanson, S. Jeffries Multidisciplinary Investigation of Stranded Harbor Porpoises (*Phocoena phocoena*) in Washington State with an Assessment of Acoustic Trauma as a Contributory Factor, International Association for Aquatic Animal Medicine
- 2005 Miller, B., D. Mountain, A. Zosuls, S. Newburg, and D. Ketten Middle and Inner Ear Stiffness Measurements in the Bottlenose Dolphin, *Tursiops truncatus*. Assoc. Res. Otolaryngol. Abs. 1175
- 2005 Moein-Bartol, S., D.R. Ketten Functional Measures of Sea Turtle Hearing, Environmental Consequences of Underwater Sound, NOPP-ONR Review, Arlington, Virginia.
- 2005 Ketten, D.; J. Arruda; S. Cramer,. O'Malley; J. Reidenberg, S. McCall; J. Craig. Experimental Measures of Blast Trauma in Marine Animals. Environmental Consequences of Underwater Sound,. NOPP-ONR Review, Arlington, Virginia

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE (DD-MM-YYYY) 08/22/2006		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 21 June, 2003 – 20 June, 2005	
4. TITLE AND SUBTITLE Models of Whale Auditory Function				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER N00014-00-10905	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Ketten, Darlene R.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution				8. PERFORMING ORGANIZATION REPORT NUMBER WHOI Proposal Number BI10702	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Dr. Robert Gisiner Office of Naval Research 875 Randolph Street, Suite 1425 Code 341 Arlington, VA 22217-5660				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT approved for public release; distribution is unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <p>The specific objective of this project was to develop biophysically based models of the inner and middle ear of a range of marine mammals to allow us to estimate audiograms from anatomical and mechanical measurements. This project was designed to provide modular data to be integrated with the methodologies and partnership projects developed under the ONR Effect of Sound in the Marine Environment (ESME) Program. The effort involved an integration of anatomical and physiological data. Anatomical analyses (WHOI/D.R. Ketten) characterized head, middle, and inner ear structures of representative odontocete species. Physiological Modeling (BU/ David Mountain) implemented auditory response models using the anatomical data. This is the requisite first-step towards developing species-specific TTS models.</p>					
15. SUBJECT TERMS <p>Cetacea, Marine Mammals, Beaked Whales, Acoustic Impedances, FEM, Inner Ear, Middle Ear, Cochlea, Model, MRI, CT, Three-D Imaging</p>					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Darlene R. Ketten
					19b. TELEPHONE NUMBER (Include area code) 508-289-2731